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13. ABSTRACT (Maximum 200 words)

The object of this research was to develop and evaluate a formal measure of shape similarity that could predict human performance in recognizing and discriminating highly similar complex shapes and objects. The similarity measure is the correlation in activation values over a lattice of columns of Gabor filters (termed "Gabor Jets"). Each column is composed of a number of filters at different scales and orientations, all centered on the same position in the visual field, similar to cortical hypercolumns (Lades et al., 1993). For amoeboid blobs, infrared images of tanks, and faces, high correlations were obtained between the similarity measure and psychophysical discrimination/identification performance. To our knowledge, this is the first time that the similarity of complex shapes has been determined directly from a measure of the shapes themselves. A different similarity basis is required, however, when distinctive nonaccidental properties are available. We present rigorous evidence for the employment of NAPs in object recognition (Biederman & Bar, 1998) and the preferential tuning of cells in the inferotemporal cortex to NAPs (Vogels, Biederman, bar, and Lorincz. 2000). These findings have provided the bases for an integrated account of basic- and subordinate level object classification combining geon theory with the Gabor Jet model (Biederman & Kalocsai; 1987).

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Abstract. The object of this research was to develop and evaluate a formal measure of shape similarity that could predict human performance in recognizing and discriminating highly similar complex shapes and objects. The similarity measure is the correlation in activation values over a lattice of columns of Gabor filters (termed “Gabor Jets”). Each column is composed of a number of filters at different scales and orientations, all centered on the same position in the visual field, similar to cortical hypercolumns (Lades et al., 1993). For amoeboid blobs, infrared images of tanks, and faces, high correlations were obtained between the similarity measure and psychophysical discrimination/identification performance. To our knowledge, this is the first time that the similarity of complex shapes has been determined directly from a measure of the shapes themselves. A different similarity basis is required, however, when distinctive nonaccidental properties are not available. We present rigorous evidence for the employment of NAPs in object recognition (Biederman & Bar, 1998) and the preferential tuning of cells in the inferotemporal cortex to NAPs (Vogels, Biederman, bar, and Lorincz. 2000). These findings have provided the bases for an integrated account of basic- and subordinate level object classification combining geon theory with the Gabor Jet model (Biederman & Kalocsai; 1987).

Overview of Major Results

The object of this research was to develop and evaluate a formal measure of shape similarity that could predict human performance in recognizing and discriminating highly similar complex shapes and objects. Remarkably, we succeeded. The similarity measure is the correlation in activation values over a lattice of columns of Gabor filters (termed “Gabor Jets”). Each column is composed of a number of filters at different scales and orientations, all centered on the same position in the visual field. Such a scheme is presumed to be a simplified model of early cortical filtering, where the hypercolumns are arranged in a lattice superimposed over the image (Lades et al., 1993). In a sequential same-different task of a subset of the more similar pairs of the Shepard & Cermak (1973) toroidal "free-form" blobby shapes, the similarity measure correlated in the mid -.90s with the RTs and error rates in judging that a pair of shapes were different, without estimating any free parameters (Biederman & Subramaniam, 1997). To our knowledge, this is the first time that the similarity of complex shapes has been determined directly from a measure of the shapes themselves. High correlations were also noted (Biederman, Kalocsai, & O'Kane, 1998) between the measure of shape and psychophysical measures of face similarity (Biederman and Kalocsai (1997) and in the confusion matrix when identifying infrared images of military vehicles (O’Kane, Biederman, Cooper, & Nystrom, 1997). The Gabor Jet model enjoys its greatest success for difficult discriminations when distinctive nonaccidental properties are not available. The ability of the Gabor Jet model to predict discrimination performance is greatly reduced when objects are viewed at different orientations in depth and/or nonaccidental (i.e., viewpoint invariant) properties are available. Several studies have provided rigorous evidence for the employment of NAPs in object recognition (Biederman & Bar, 1998) and the preferential tuning of cells in the inferotemporal cortex to NAPs (Vogels, Biederman, bar, and Lorincz. 2000). These findings have provided the bases for a theory that integrates geon theory with the recognition of basic and subordinate level object classification (Biederman & Kalocsai; 1987; Biederman, et al., 2000).

We have investigated whether a computer vision system for face recognition developed by von der Malsburg and his associates (Lades et al., 1993; Wiscott, et al., 1997; see Fiser, Biederman, & Cooper, 1996, for a more extended overview) could model human performance when making difficult shape discriminations. We were particularly interested in this system because it was designed to reflect the early cortical processing of images and it was successful at actually doing face recognition. A version of this system has recently won a DARPA national competition for face recognition systems, with a level of performance that would have been undreamed of just a few years ago: In a gallery of several thousand faces, the system was 95% correct in matching a probe face to a target that could differ moderately in pose and expression. The question was whether it would provide a basis for for representing the psychophysical similarity of complex shapes, such as faces, infrared images of military vehicles, and unfamiliar blobs in shape discrimination and recognition tasks. We also explored the conditions under which it would not predict psychophysical performance.

The Gabor Jet Model. The model (Figure 1) first filters the image according to columns of Gabor filters, termed a Gabor "jet." Each jet contains filters at, say, 5 scales and 8 orientations, for a total of 40 kernels (in this example). (Each kernel actually comes as sine and cosine but we will ignore that aspect in this brief overview.) Each jet is centered on a position in the visual field at the vertices of a lattice of, say, 6 rows X 8 columns, that covers the object. [There is automatic normalization for position, size, and overall contrast.] The lower frequency kernels cover much of the object and thus are highly sensitive to the configuration of features. To put it in neural terms, each jet would correspond to a hypercolumn of the initial spatial processing in the hypercolumns in the visual cortex. The activation of each cell (= kernel) is a function of the tuning (i.e., receptive field) of that cell to the orientation and scale of the contrast in that portion of the visual field.

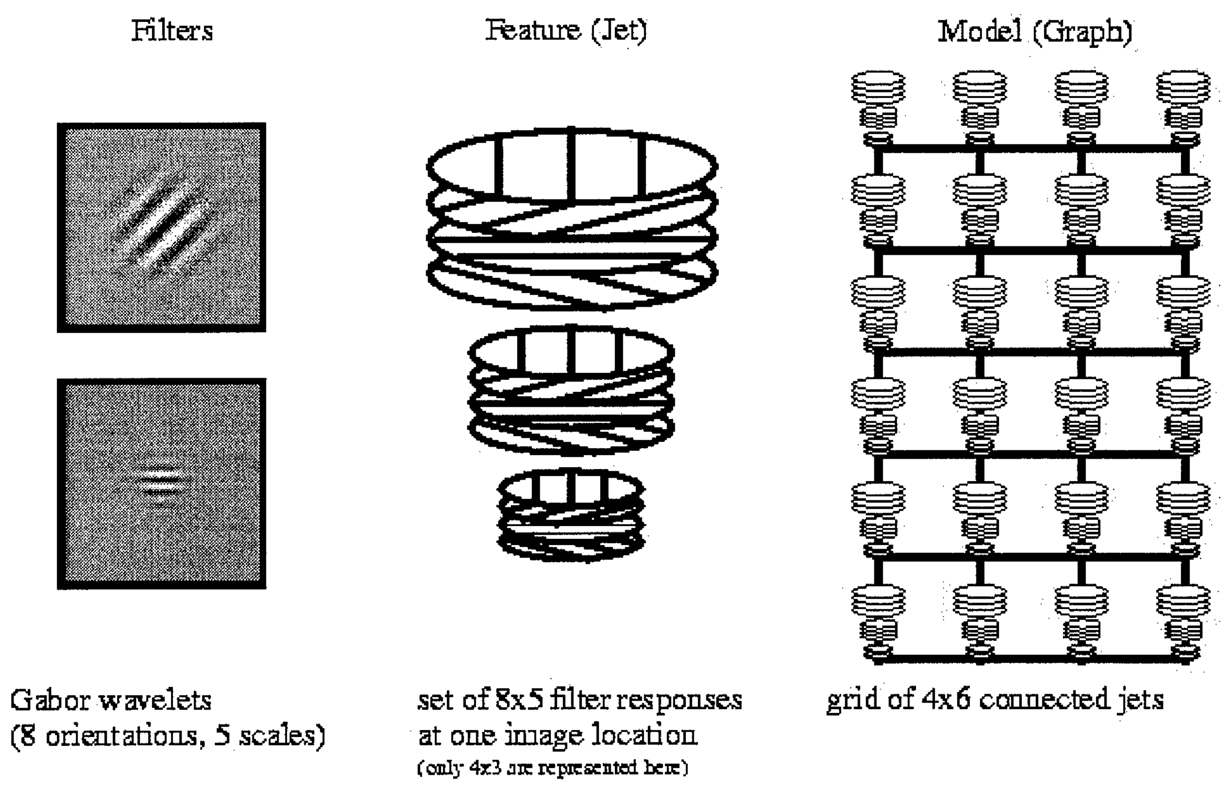


Figure 1. Illustration of the input layer to the Lades et al. (1993) network. The basic kernels are Gabor filters at different scales and orientations, two of which are shown on the left. The center figure illustrates the composition of a jet, with the larger disks representing lower spatial frequencies. The number of jets, scales, and orientation can be varied. (From Biederman & Kalocsai, 1997.)

A similarity measure is derived by correlating, for each jet in the image, the amplitudes of the 40 kernels of that jet, with the corresponding kernels of the corresponding jet in a stored image. This correlation can be expressed as the cosine between two-40 element vectors. Given a set of stored images, the one with the highest correlation to the probe image, if it exceeds some minimum value, would be taken to be the best match. An option is to allow simulated annealing in which the jets can undergo modest variation in their position, though at some cost, to maximize the correlation. The final positions for nonidentical images would result in a deformation of the original lattice as shown in Fig. 6 for tanks and Fig. 7 for faces. Although such a stage results in higher absolute simiilarity values, the ordering of the similarity of the images is only rarely affected by the annealing. Thus, if image A is more similar to image B than it is to C before annealing, almost always the same relations will hold after annealing. I have included the annealing stage in Figure 6 and 7 to illustrate the best fitting distorted meshes.

PREDICTING THE PSYCHOPHYSICAL SIMILARITY OF NOVEL COMPLEX SHAPES

1. Discriminating the Shepard and Cermak (1973) shapes.

We (Biederman & Subramaniam, 1997) have demonstrated that the Gabor Jet model can predict, virtually perfectly, the speed and accuracy required to discriminate (as Same or Different) a sequentially presented pair of asymmetrical, unfamiliar, blobby shapes, devised by Shepard and Cermak (1973) and shown in Fig. 2. The Gabor Jet scaling of the distances of the shapes is illustrated in Fig. 3. We used a task illustrated in Fig. 4. (A similar sequential same-different task was used to assess the degree to which similarity values derived from the Gabor Jet model would predict psychophysical similarity of faces.)

As illustrated in Figure 4, subjects had to judge whether a pair of highly similar shapes were same or different. For similar shapes (those pairs with a similarity value of .82 and higher) the correlation between model similarity values and RTs and error rates on Different trials was .96 and .95, respectively, as shown in Fig. 5. These are extraordinary high values given that no free parameters were fixed according to the performance of the subjects. In fact, it is the first time that performance in discriminating complex shapes was predicted quantitatively from a theoretical model.

When we investigated the full range of similarities, from 68 to 95, a bilinear relationship was evident, as is shown in Fig. 6. Why? Consider in Fig. 2, the difference in the left lobes between H1 and F4. H1's is squarish; F4's is pointy. That difference, a difference in nonaccidental properties (NAPs) is typical between those pairs of shapes that are more dissimilar (i.e., lower) than 82. (NAPs are properties of images that do not change with rotation in depth, such as whether a line is straight or curved.) Shepard and Cermak (1973) had their subject provide interpretations of the shapes in Fig. 2. Very close shapes tended to differ only metrically, e.g., in the degree of bulge of a lobe. Such shapes tended to have the same interpretation, e.g., as a bird looking left; a stone axe; a cat looking right; Africa. Shapes at a greater distance, i.e., lower Gabor Jet similarity, tended to have different interpretations. By our scaling, the average Gabor Jet distance at which the interpretation would change was .82. The implication of this result is that a change in a NAP invites a change in a visual concept.

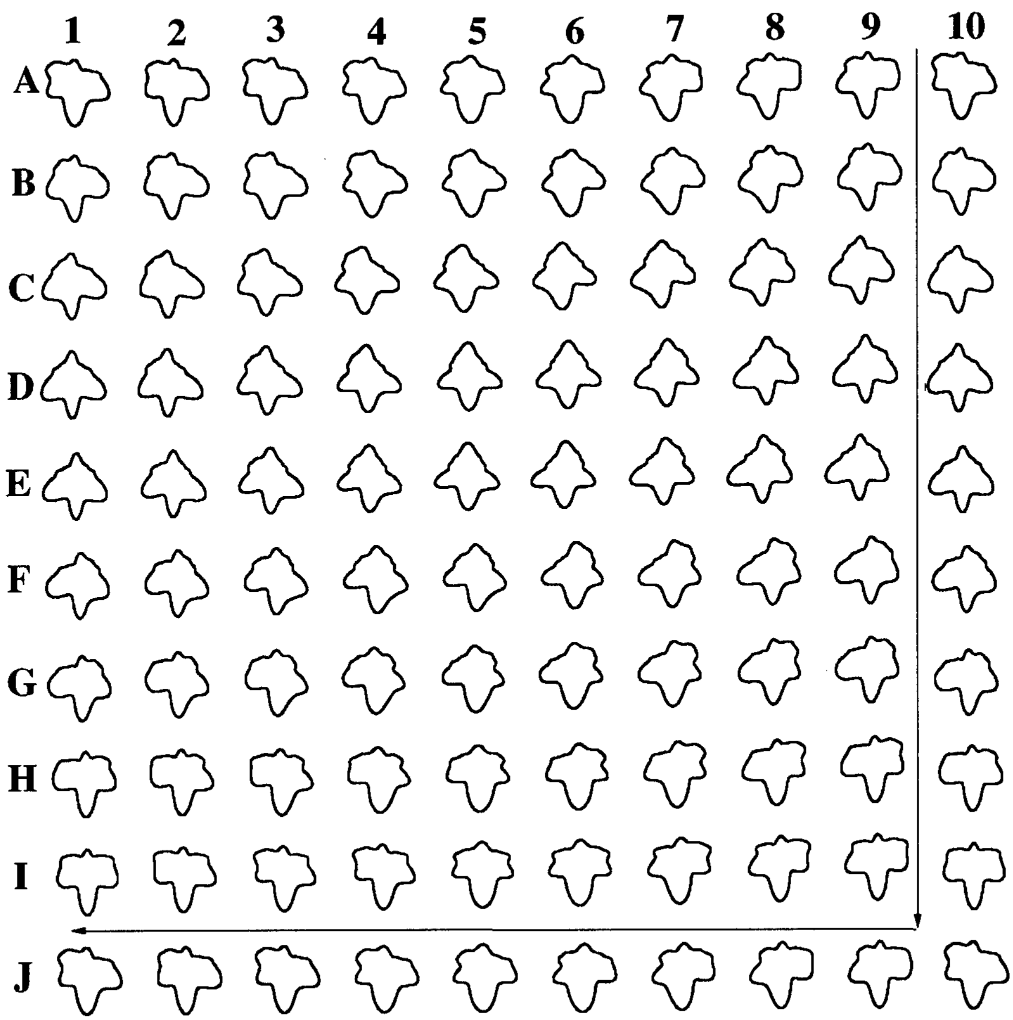


Figure 2. The complete set of stimuli used in the experiments. The bottom row (J) is identical to the the top row (A) and the rightmost column (10) is identical to the leftmost column (1) implying that the array is topologically equivalent to the two dimensional surface of a torus or a doughnut. (Adapted from Shepard & Cermak, 1973.)

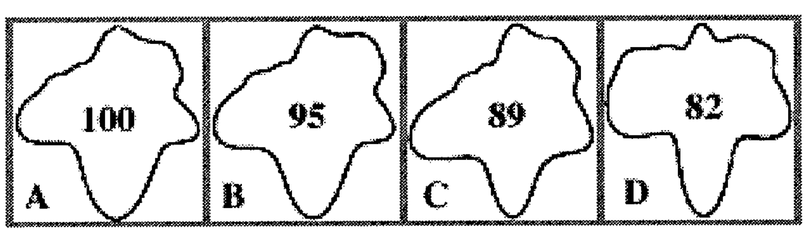


Figure 3. Illustration of four of the 81 Shepard and Cermak (1973) free-form shapes. The similarity values from the Gabor Jet model (Lades et al., 1993) for each of the shapes with respect to A are shown in the shapes.

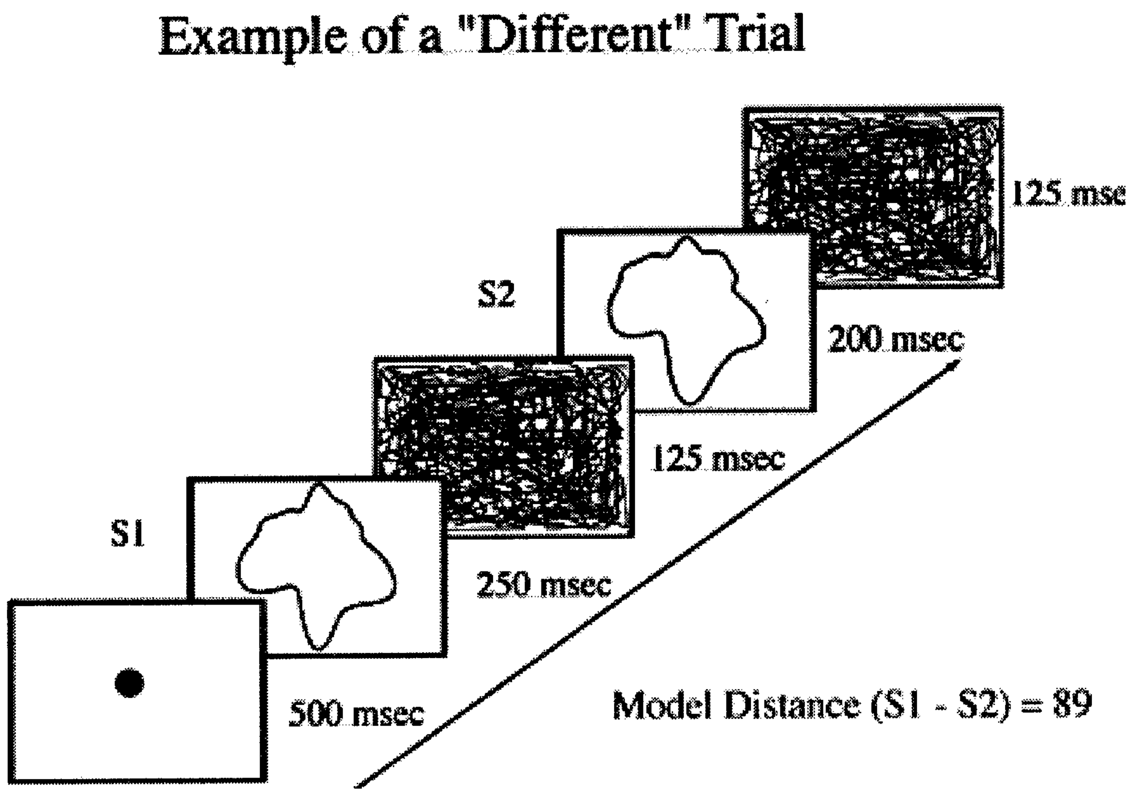
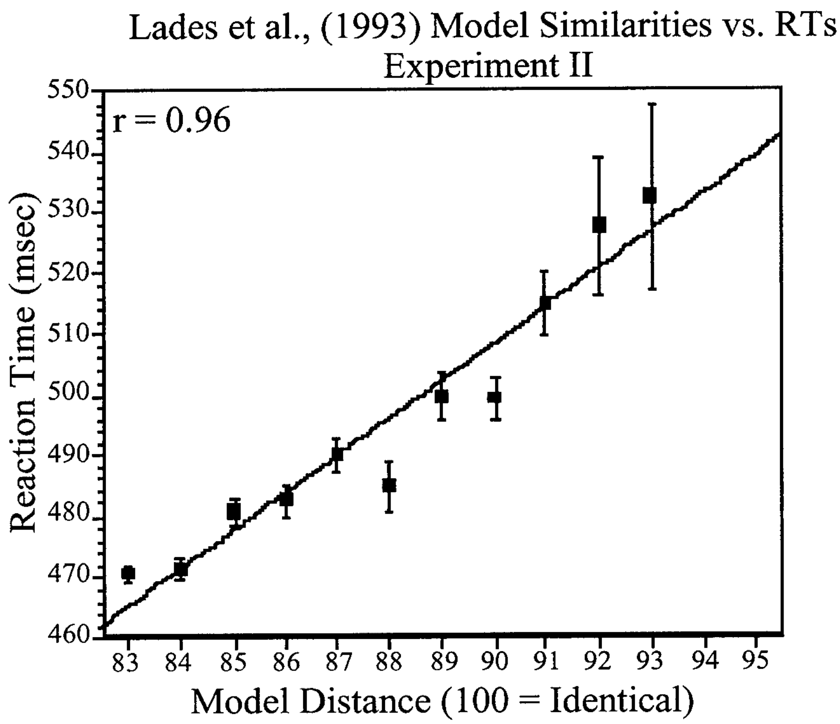


Figure 4. Illustration of a single ("Different") trial from Subramaniam, et. al (2000) for a pair of shapes with a similarity value of .89. The experiment assessed the correlation between similarity values derived from the Gabor Jet model for a set of free form shapes and human performance in discriminating those shapes. In the actual experiment, S2 was displaced slightly from S1, even on Same trials so that subjects could not use a displacement cue to make their judgment that the shapes were different.



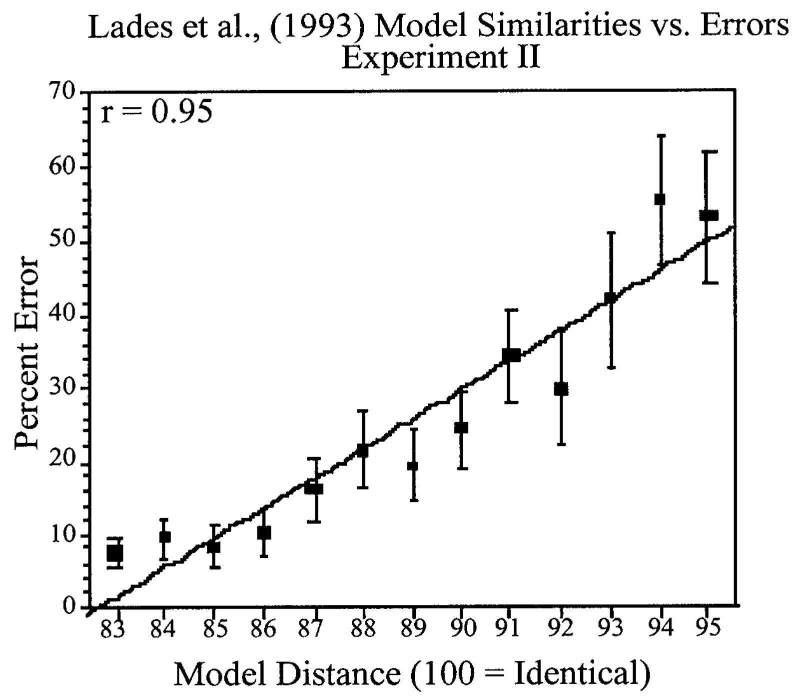
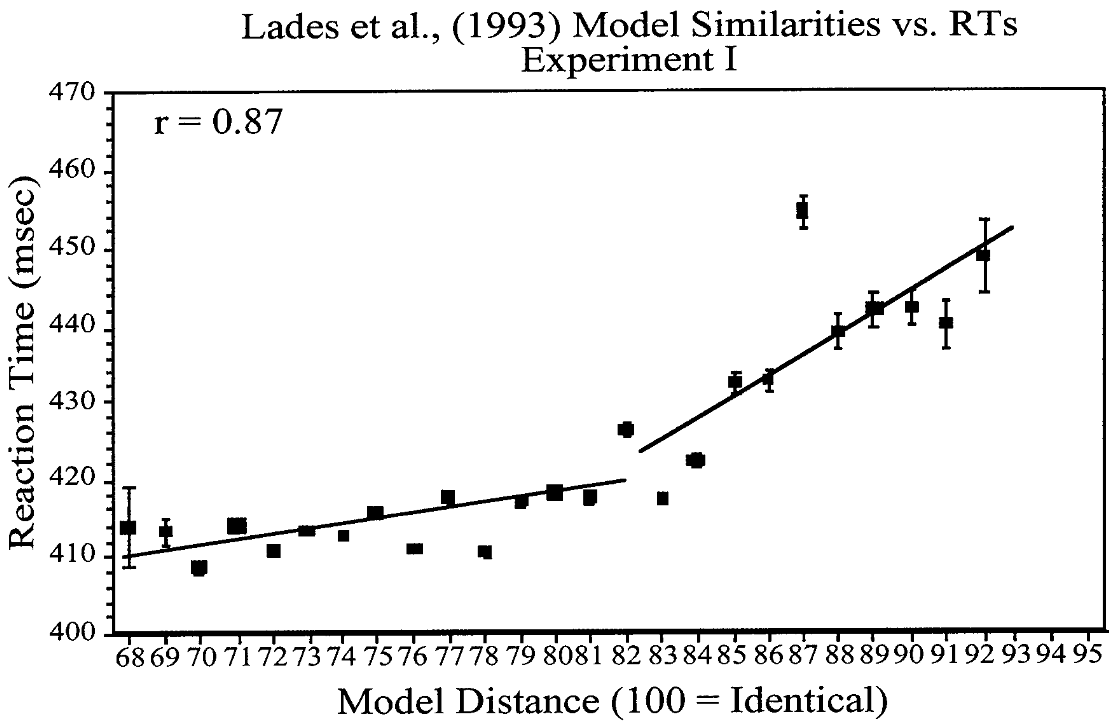


Figure 5. RTs and error rates plotted as a function of the Lades et al., (1993) wavelet similarity measure over the restricted range. The best fitting lines for the data are also shown. Correlations were 0.96 and 0.95 for RTs and error rates, respectively.



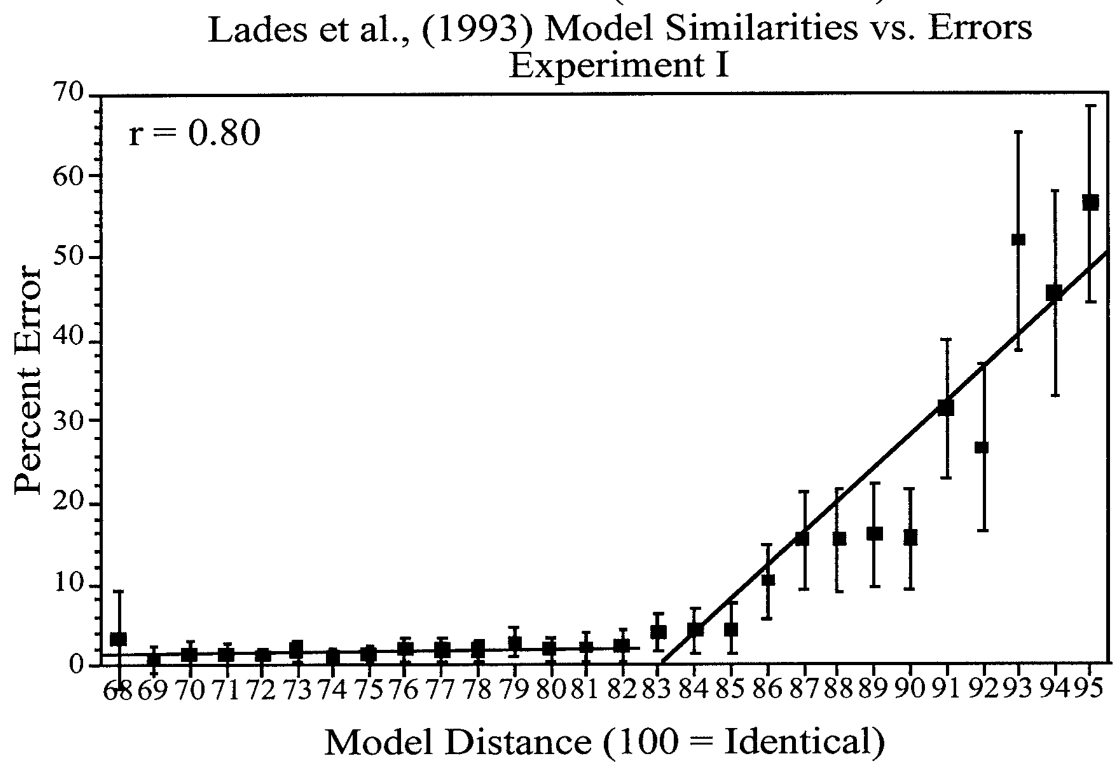


Figure 6. RTs and error rates plotted as a function of the Lades et al., (1993) wavelet similarity measure. The best fitting lines highlighting the bilinear structure of the data are also shown. Correlations were 0.87 and 0.80 for RTs and error rates, respectively.

2. Identifying Infrared Images of Military Vehicles

O'Kane, Biederman, Cooper, &Nystrom (1997) studied the confusion errors that trained military observers, e.g., tank crews, made in attempting to identify infrared images of 15 military vehicles, such as tanks, APCs, jeeps, and trucks. A similarity tree (not shown) was generated based on judged differences in the parts and the distinctiveness of the differences, with distinctiveness defined in terms of the scale and nonaccidentalness of the difference. That is, large and/or nonaccidental differences in shape occupied a higher position in the tree (therefore were at greater nodal distances) than small and/or metric differences. The fewer the number of nodes separating two vehicles, the greater the number of confusions. Although such a tree provides an excellent means of instruction and was strongly correlated with confusion errors, it was possible to account for the confusion errors by scaling the differences according to the Gabor Jet model. Figure 7 provides an some sample images from the experiment and their confusion rates with a T62 tank. The similarity values were obtained from close up and low noise images as shown in Fig. 7 but the data came from an identification task performed on images taken from much greater distances and very high noise levels as shown in Fig. 8 (O'Kane, Biederman, & Cooper, 1997). The Gabor Jet similarity measure correlated .81 with the confusion matrix. This result suggests that the model preserves essential characteristics of shape under degraded viewing conditions. This value, .81, is uncorrected for the unreliability in the confusion matrix itself. That is, if we were to replicate the experiment, we would not find the exact same values in the confusion matrix but they would differ somewhat from the original values. This variability is error variance and connot be predicted. Consequently, the value of r = .81, which thus accounts for 64% of the variance (r^2 = proportion of variance predicted), is a lower bounds estimate of the proportion of the total variance(= predictable variance + error variance) that is *predictable* by the Gabor Jet measure.

3. Matching Faces without Easy Features

Biederman and Kalocsai (1987) investigated same-different judgment of faces that were either at different orientations, different expressions, or both. The faces on a given trial were of the same sex, age, and race with the hairline concealed and had no easy distinguishing features such as facial hair, glasses, etc, as shown in Fig. 9. In a task similar to that shown in Fig. 4, subjects judged whether the pair of images were the same individual or not. Different orientations and expressions reduced the similarity of the images Pairs of images were scaled according to the Gabor Jet model. For Same trials, RTs and error rates were highly negatively correlated (-.90+) with the Gabor Jet similarity values.

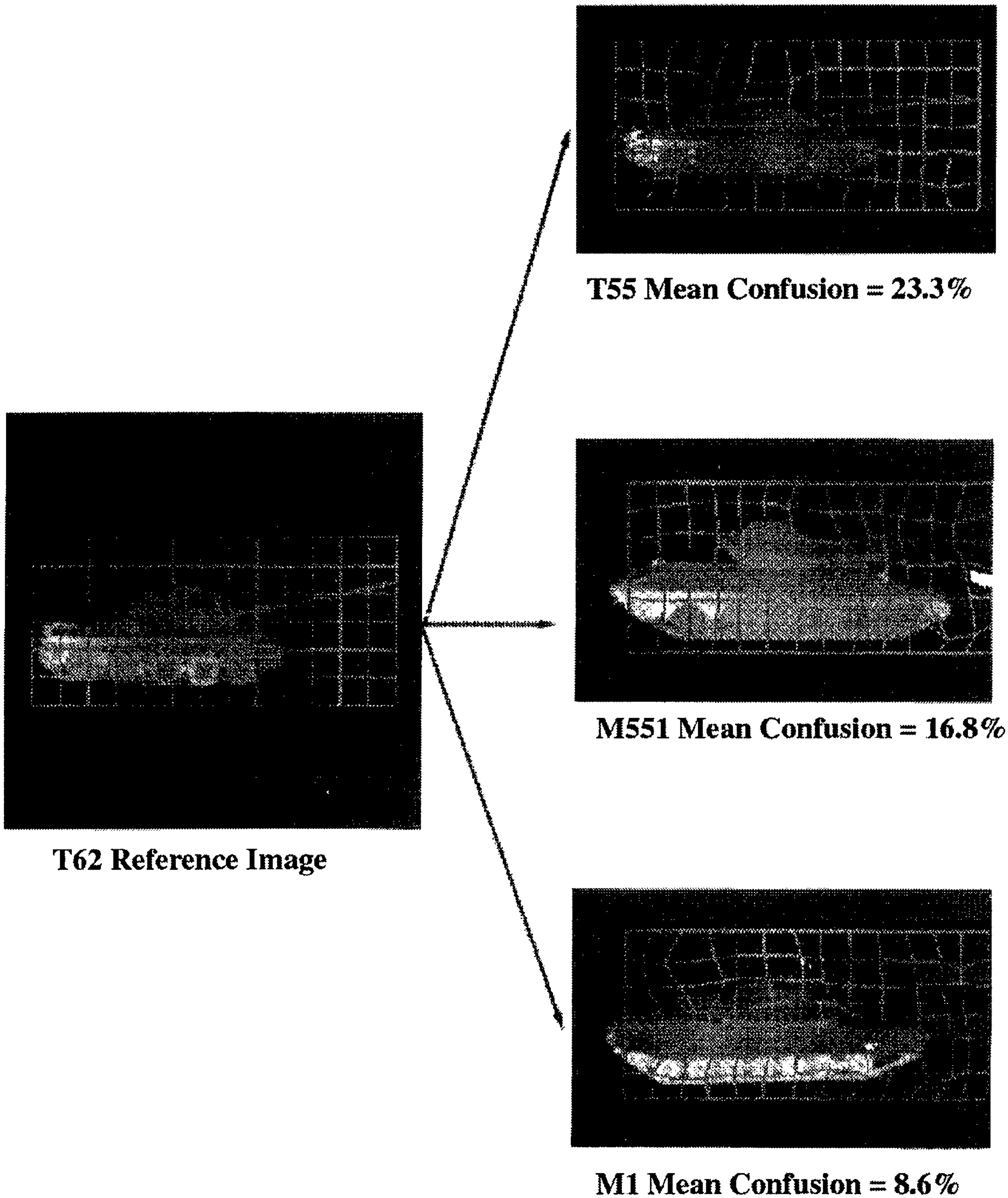


Figure 7. The confusion rates for three tanks with the T62. The original reference image is the T62 showing the regular rectangular mesh (7 X 14 in this case) with the jets positioned at each of the nodes according to the Gabor Jet model (Lades et al., 1993). The best fitting jet positions for the comparison tanks produce a distorted mesh with the magnitude of the distortion reflecting the degree of dissimilarity. An identical image matched against itself would have a similarity value of 1. The values for the T55, M551, and M1 were .85, .79, and .80, respectively. In this case, the model did not reflect the relatively high confusion rate of the M551 with the T62 compared to the M1. In general, however, the correlation between model similarity value and confusion rate was quite high = .81. From O'Kane, B. L., Biederman, I., Cooper, E. E., & Kalocsai, P. (1996).

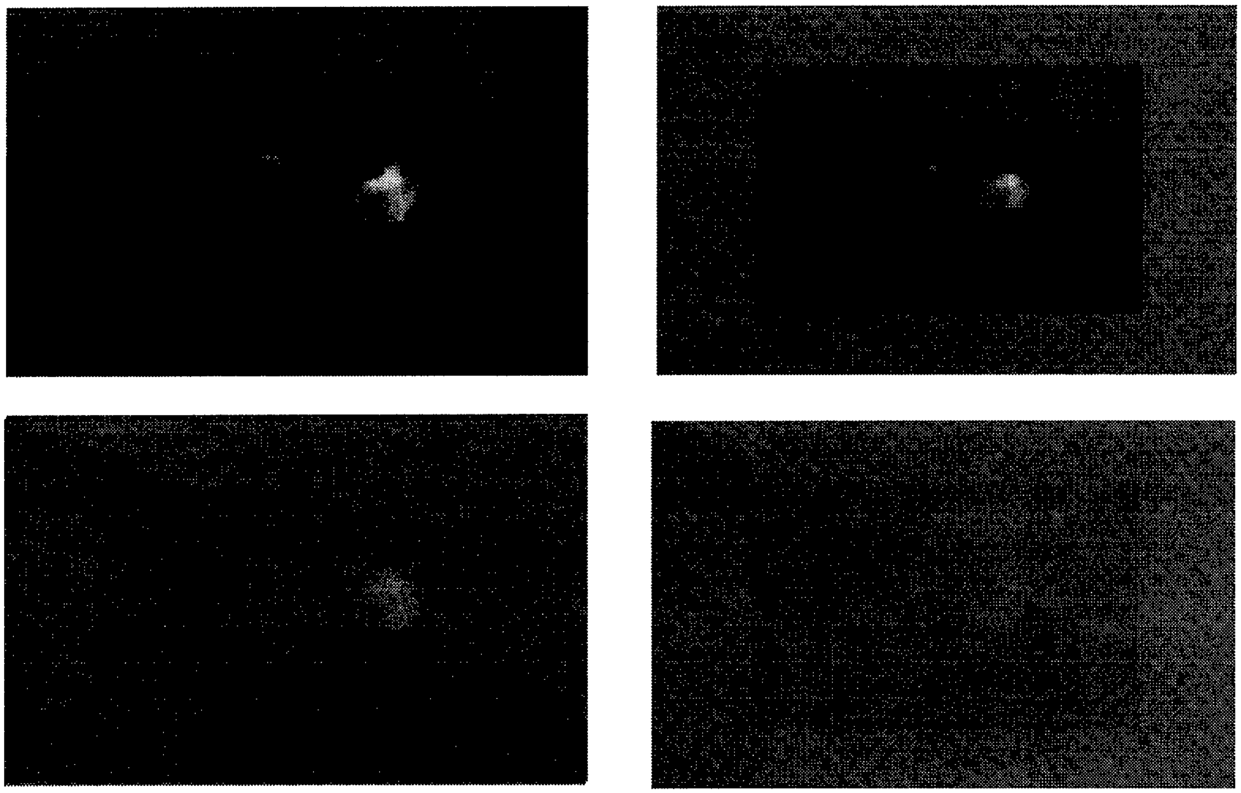


Figure 8. Sample of near (left column) and far ranges (right column) and low noise (top row) and high noise (bottom row) used in the O'Kane, B. L., Biederman, I., Cooper, E. E., & Kalocsai, P. (1996) experiments.

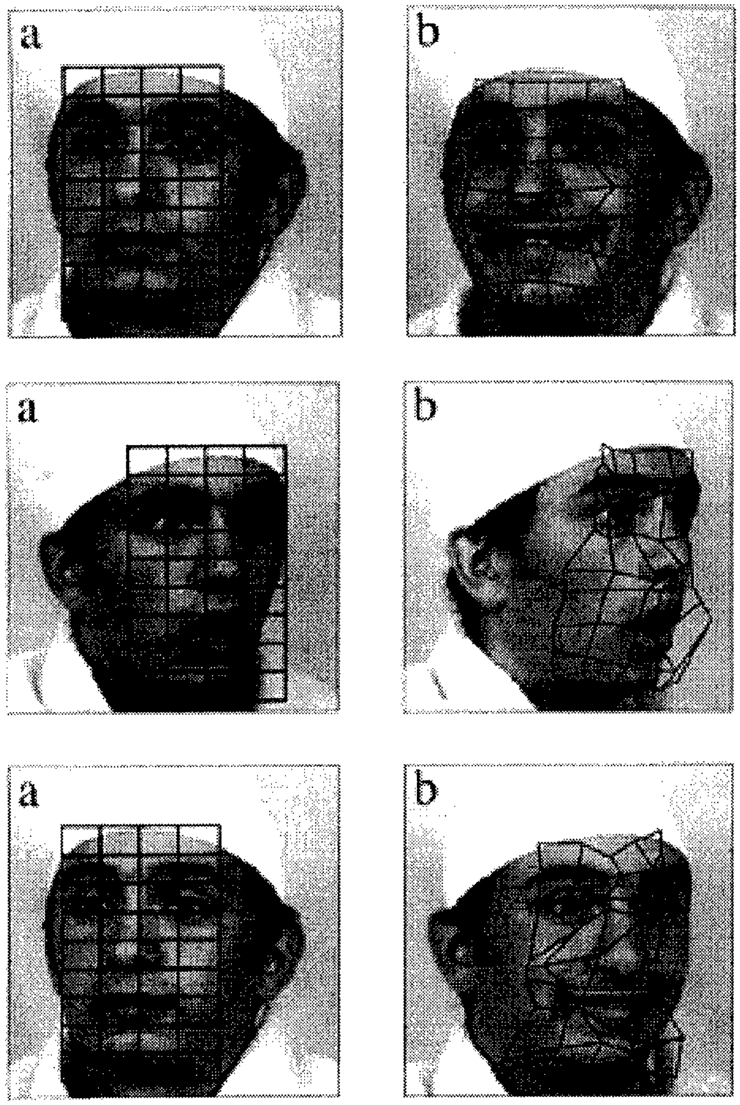


Figure 9. The positioning of the (Lades et al., 1993) lattice over an original image is shown in the left-hand column (a). The result of the diffusion over a pair of faces is shown in the right column (b). From top to bottom, the rows illustrate a change in expression, orientation, and both expression and orientatoin. In general the more distorted the grid, the more dissimilar the iamges of the two faces. In a task where subjects have to judge whether two faces images are of the same person, the Gabor Jet similarity values are well correlated with the RTs and error rates in judging that two images are of the same person: The greater the similarity, the easier it is to judge that two images of the same individual are the same person and the more difficult it is to judge that images of different people are, in fact, different. (From Kalocsai & Biederman, 1996.)

IV. Comparing NAPs and MPs in Object Recognition

Bar, M., & Biederman, I. (1999). One-shot viewpoint invariance in matching novel objects. *Vision Research*, 39, 2885-2899..

Humans show an extraordinary competence at recognizing objects from arbitrary orientations in depth. According to one class of theories, this competence is based on previously having learned different templates, expressing the metric properties (MPs) at the different orientations. An alternative class of theories assumes that nonaccidental properties (NAPs) can be exploited so that even novel objects can be recognized under depth rotation. Same-Different judgments of a sequential pair of novel rotated objects, differing in a MP or a NAP (when different) (Fig. 10), viewed only once by each subject, revealed complete depth invariance when objects differed in a NAP. The sequence of events on a trial are illustrated in Fig. 11. Following a press of the mouse button, a fixation dot appeared for 500 ms, followed by a 400 ms presentation of the object, which was then immediately followed by a mask consisting of a combination of different gray-level objects presented for 500 ms. A second object image was then presented for 300 ms, followed by a second 500 ms mask. The second stimulus was translated randomly over nine possible positions on the screen, specified by a three by three matrix with adjacent horizontal or vertical centers separated by 6.8°. Thus, the second image could be above or below, and/or, to the right or to the left of the first image which was always centered. Rotation dramatically reduced the detectability of MP differences to a level well below that expected by chance (12). NAPs offer a striking advantage over MPs for object classification and are therefore more likely to play a central role in the representation of objects.

Vogels, R., Biederman, I., Bar, M, & Lorincz, A. (2000). Inferior temporal neurons show greater sensitivity to nonaccidental than metric differences. *Journal of Cognitive Neuroscience*, in press..

It has long been known that macaque inferior temporal (IT) neurons tend to fire more strongly to some shapes than to others, and that different IT neurons can show markedly different shape preferences. Beyond the discovery that these preferences can be elicited by features of moderate complexity, no general principle of (non-face) object recognition had emerged by which this enormous variation in selectivity could be understood. Psychophysical as well as computational work suggests that one such principle is the difference between viewpoint-invariant, non-accidental (NAP) and view-dependent, metric shape properties (MPs). Vogels et al. (2000) measured the responses of single IT neurons to objects differing in either a NAP (namely, a change in a geon) or a MP of a single part, shown at two orientations in depth. The images were those from Biederman and Bar (1999). The cells were more sensitive to changes in NAPs than in MPs, even though the image variation (as assessed by wavelet-like measures) produced by the former were smaller than the latter. The magnitude of the response modulation from the rotation itself was, on average, similar to that produced by the NAP differences, although the image changes from the rotation were much greater than that produced by NAP differences. Multidimensional scaling of the neural responses indicated a NAP/MP dimension, independent of an orientation dimension. The present results thus demonstrate that a significant portion of the neural code of IT cells represents differences in NAPs rather than MPs. This code may enable immediate recognition of novel objects at new views.

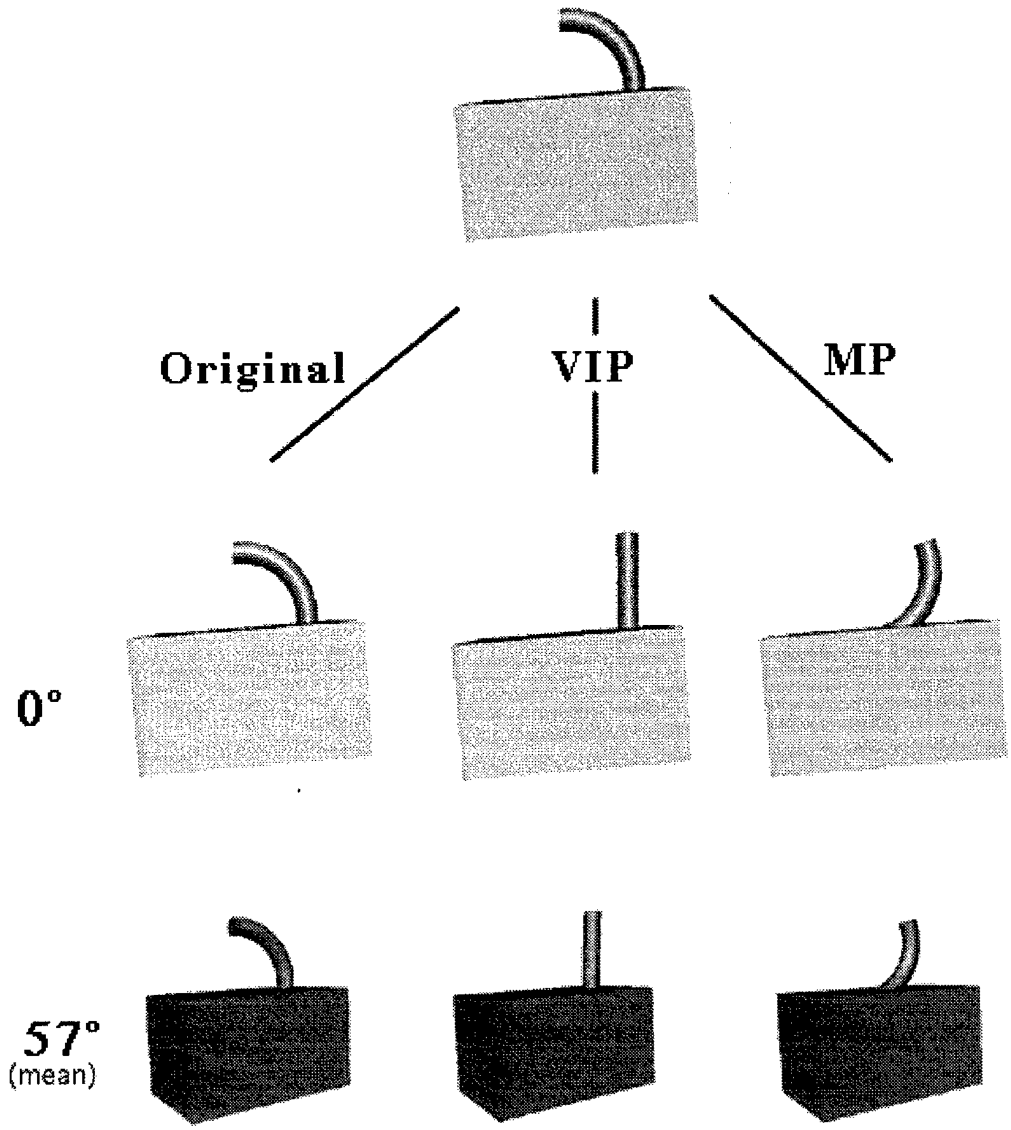


FIG. 10 An example of possible variations from the original version in the calibration and rotation phases. The VIP change is one of a curved to straight cylinder. The MP change is a change in the degree of curvature of the cylinder. In the calibration phase (0°) the objects are depicted from identical orientations, with the magnitude of the VIP and MP changes selected to yield equal detectabilty as shown on the 0° value in Fig. 4. In the rotation phase, objects were rotated (an average of) 57°. The differences in surface lightness between the two orientations is a consequence of a single light source used in the rendering (which provided a potential cue as to the degree of rotation).

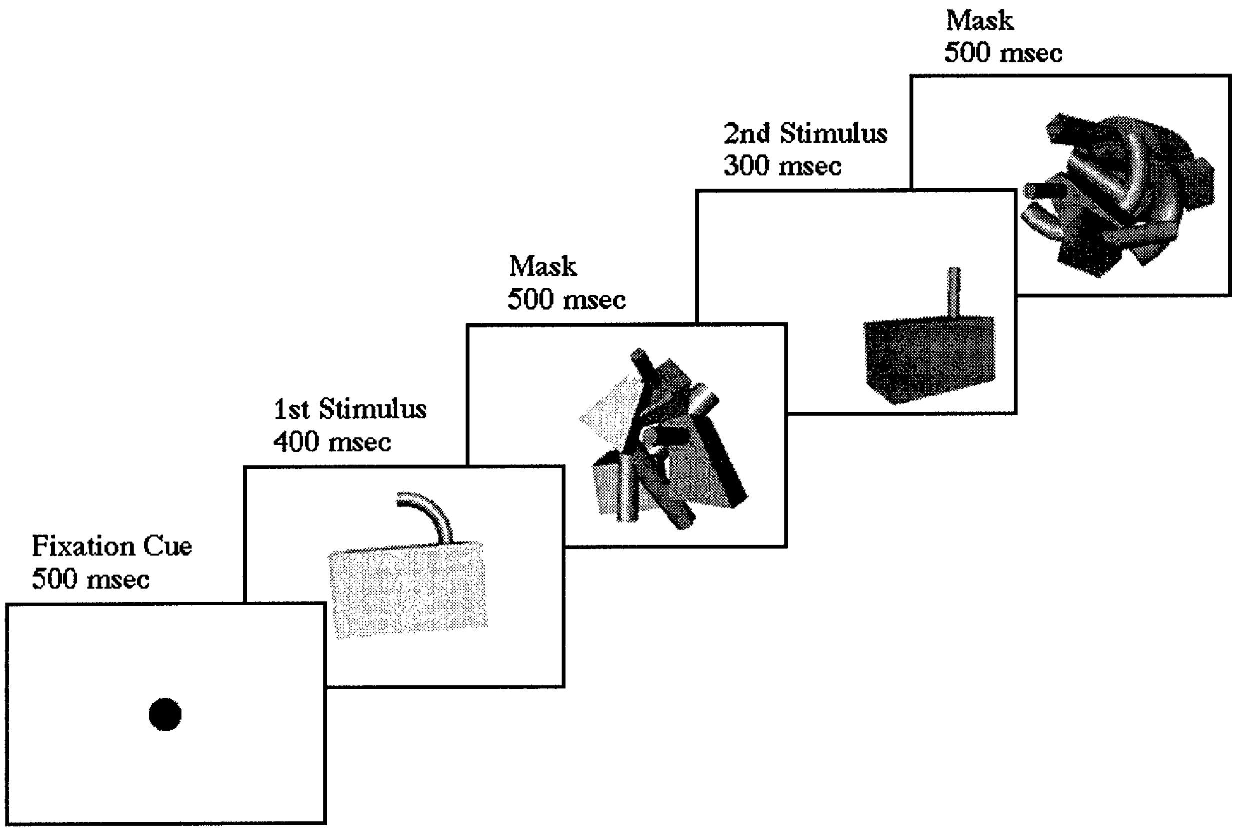
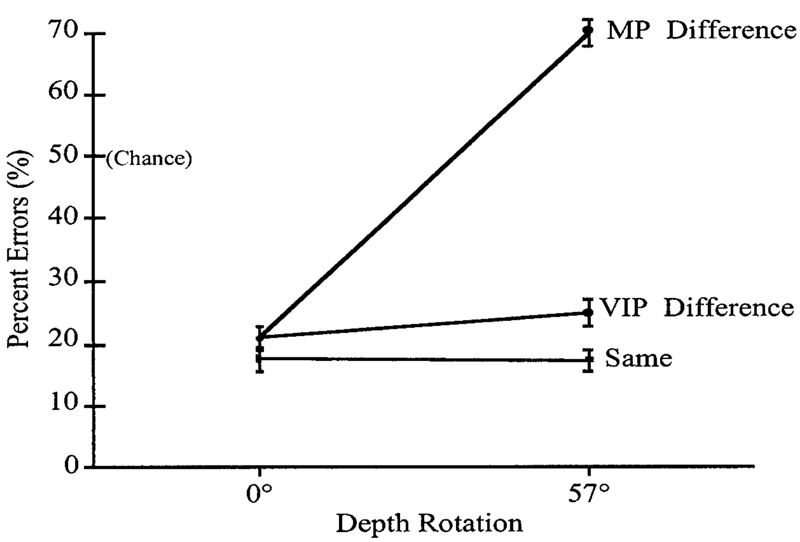


FIG. 11 Sequence of events on an experimental trial. An illustration of a VIP DIFFERENT trial in the rotation phase of the experiment. The sequence would be the same in the calibration phase. Note the shift of the second object to the lower right, relative to the position of the first object.



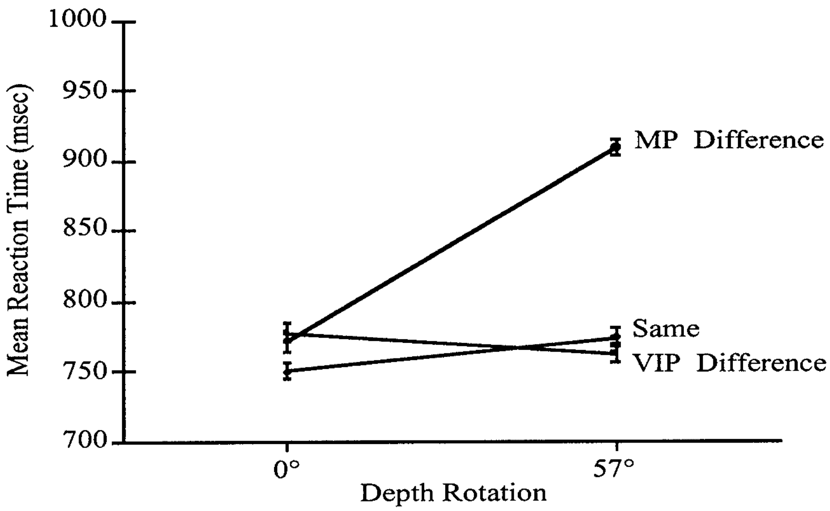


FIG. 12. Mean error rates (upper panel) and mean correct reaction times (lower panel) for 10 subjects as a function of differences in orientation and the type of difference (Same, MP Different, and VIP Different). RTs greater than 2,000 msec were counted as errors. Error bars are the S.E.s when variance attributable to main effects of subjects and objects are removed.

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(All are available from the P.I., Professor Irving Biederman, bieder@usc.edu.)

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Kalocsai, P., & Biederman, I. (1997). Biologically inspired recognition model with extension fields. *Proceedings of the 4th Joint Symposium on Neural Computation*, pp. 116-123, University of California, San Diego.

O'Kane, B., Biederman, I., Cooper, E. E., & Nystrom, B. (1997). An account of object identification confusions. *Journal of Experimental Psychology: Applied*, 3, 21-41.

Kalocsai, P., & Biederman, I. (1997). Biologically inspired recognition model with extension fields. *Proceedings of the 4th Joint Symposium on Neural Computation*, pp. 116-123, University of California, San Diego.

Fiser, J., Biederman, I., & Cooper, E. E. (1996). To what extent can matching algorithms based on direct outputs of spatial filters account for human shape recognition? *Spatial Vision*, 10,

Biederman, I., & Gerhardstein, P. C. (1995). Viewpoint-dependent mechanisms in visual object recognition: Reply to Tarr and Bülthoff (1995). *Journal of Experimental Psychology: Human Perception and Performance*, 21, 1506-1514.

Fiser, J., & Biederman, I. (1995). Size invariance in visual object priming of gray scale images. *Perception*, 24, 741-748.

Fiser, J., Biederman, I., & Cooper, E. E. (1995). Test of a two-layer network as a model of human entry-level object recognition. Pp. 391-396. J. M. Bower (Ed.) *The Neurobiology of*

Computation: Proceedings of the Third Annual Computational Neuroscience Meeting. Boston: Kluewer.

Biederman, I. (1995). Visual object recognition. In S. M. Kosslyn and D. N. Osherson (Eds.). *An Invitation to Cognitive Science*, 2nd edition, *Volume 2, Visual Cognition.* MIT Press. Chapter 4, pp. 121-165.

Biederman, I. (1995). Geon theory as an account of shape recognition in mind, brain, and network. *Cognitive Studies: Bulletin of the Japanese Cognitive Science Society*, 2, 46-59.

Biederman, I. (1995). Some Problems of Visual Shape Recognition to Which the Application of Clustering Mathematics Might Yield Some Potential Benefits. In I. J. Cox, P. Hansen, B. Julesz (Eds.) *Partitioning Data Sets,* Pp. 313-329. Providence, R. I.: American Mathematical Society.

CONFERENCE AND SYMPOSIA PRESENTATIONS

Biederman, I. (2000). Shape recognition in mind and brain. Invited address at a symposium on object recognition at the International Congress of Psychology, Stockholm, July.

Mangini, M. C., Biederman, I., Kosta, A. (2000). Is greater accuracy for gender than person discrimination of faces a consequence of class uncertainty? Evidence from normals and a prosopagnosic. Poster presented at the Meetings of the Association for Research in Vision and Ophthalmology, Ft. Lauderdale, FL., May. *Investigative Ophthalmology & Visual Science*, 41, 225.

Vessel, E. A., & Biederman, I. (2000). Brightness judgments within minimal part types are easier than between part types. Poster presented at the Meetings of the Association for Research in Vision and Ophthalmology, Ft. Lauderdale, FL., May. *Investigative Ophthalmology & Visual Science*, 41, 226.

Biederman, I. (2000). Human face and object recognition in vertebrates (man and macaque). Invited paper presented at a Workshop on Recognition of Visual Patterns and Landmarks by Insects. Delmenhorst, Germany, March.

Kosta, A., & Biederman, I. (1999). Does variability in the size of an object's parts facilitate recognition? Paper presented at the 7th Annual Workshop on Object Perception and Memory. Los Angeles.. Nov.

Vessel, E. A., Mangini, M. C., & Biederman, I. (1999). Experts vs. novices performing subordinate RSVP identification. Paper presented at the 7th Annual Workshop on Object Perception and Memory. Los Angeles. Nov.

Mangini, M. C., & Biederman, I. (1999). Do objects with many parts incur greater attentional costs than objects with few parts? Poster presented at the 7th Annual Workshop on Object Perception and Memory. Los Angeles. Nov.

Vogels, R., Biederman, I., & Bar, M. (1999) Sensitivity of macaque temporal neurons to variations in object shading. Paper presented at the Meetings of the Society for Neuroscience, Miami, FL. Nov.

Biederman, I. (1999). An Evaluation of "View-Based" vs. Geon Structural Descriptions as Alternative Accounts of Visual Object Recognition. Invited paper presented at the 2nd IEEE Workshop on Generic Object Recognition, Corfu Greece, September.

Biederman, I. (1999). Aiding image analysts through RSVP training and displays. Invited presentation at a Meeting of Neuroscience Inspired Target Recognition, The Neuroscience Institute, La Jolla, CA. September

Biederman, I. (1999). Recognizing Depth-Rotated Objects: A Review of Recent Research and Theory. Invited paper at Workshop on Visual Object Recognition by Humans and Machines, Bad Homburg, Germany, May.

Vogels, R., Biederman, I., & Bar, M. (1999) Sensitivity of macaque temporal neurons to differences in view-invariant vs. metric properties of depth-rotated objects. Paper presented at the Meetings of the Association for Research in Vision and Ophthalmology, Ft. Lauderdale, FL., May. (*Investigative Ophthalmology & Visual Science*, 40, S776.)

Vessel, E. A., Subramaniam, S., & Biederman, I. (1999). A change in contrast polarity at an L-Junction unbinds its segments. Poster presented at the Meetings of the Association for Research in Vision and Ophthalmology, Ft. Lauderdale, FL., May. *Investigative Ophthalmology & Visual Science*, 40, 810.

Mangini, M. C., Biederman, I., & Williams, E. (1999). The effect of test-context junction discontinuities in perceived lightness. Poster presented at the Meetings of the Association for Research in Vision and Ophthalmology, Ft. Lauderdale, FL., May. *Investigative Ophthalmology & Visual Science*, 40, 747.

Biederman, I., & Bar, M. (1998). Cortical localization of subliminal visual priming. Paper presented at the Annual Meeting of the Psychonomic Society. Dallas, Nov.

Peissig, J. J., Young, M. E., Jr., Wasserman, E. A., & Biederman, I. (1998). The pigeon's discrimination of single geons. Paper presented at the Annual Meeting of the Psychonomic Society. Dallas, Nov.

Mangini, M. C., Biederman, I., and Williams, E. K. (1998). Perceived lightness as a measure of perceptual grouping. Paper presented at the Annual Object Perception and Memory Meeting. Dallas, Nov.

Vessel, E., Subramaniam, S., & Biederman, I. (1998). When does variation in contrast polarity affect contour grouping in object recognition? Paper presented at the Annual Object Perception and Memory Meeting. Dallas, Nov.

Sáry, G., Kovács, G., Köteles, K., Benedek, G., Fiser, J., & Biederman, I. (1988). Selectivity variations in monkey inferior temporal neurons for intact and contour-deleted line drawings. Poster presented at the Meetings of the Society for Neuroscience, Los Angeles, CA, November.

Bar, M., & Biederman, I. (1998). Subliminal visual priming transfers within but not between visual quadrants. Poster presented at the Meetings of the Society for Neuroscience, Los Angeles, CA, November.

Biederman, I. (1998). The neurocomputational basis of face and object recognition. Invited presentation at the Stockholm Workshop on Computational Vision, Rosenön, August 4-7, 1998.

Biederman, I., & Bar, M. (1998). Same-different matching of depth-rotated objects. . Paper presented at the Meetings of the Association for Research in Vision and Ophthalmology, Ft. Lauderdale, FL., May. *Investigative Ophthalmology & Visual Science*, 39, 1113.

Bar, M., & Biederman, I. (1998). Evidence that representations mediating subliminal visual priming are localized in an intermediate visual area such as V4. Poster presented at the Meetings of the Association for Research in Vision and Ophthalmology, Ft. Lauderdale, FL., May. *Investigative Ophthalmology & Visual Science*, 39, 1113.

Subramaniam, S., Yokosawa, K., & Biederman, I. (1998). Vertex binding and attention to 2-D shapes. Poster presented at the Meetings of the Association for Research in Vision and Ophthalmology, Ft. Lauderdale, FL., May. *Investigative Ophthalmology & Visual Science*, 39, 854.

Biederman, I. (1998). A neurocomputational basis for the difference in the representation of faces and objects. Invited presentation at the Third Annual Cognitive Science Symposium, University of California, Riverside.

Biederman, I. (1998). Why faces and objects are represented differently: A neurocomputational analysis. Invited address presented at the Inaugural Conference for the Institut des Sciences Cognitives, Lyon, France. April.

Biederman, I. (1998). Three-dimensional object representation and recognition. Invited position paper at a Symposium on Visual Object Recognition: Theory and Experiment (VORTEX). Los Angeles, CA, February.

Bar, M., & Biederman, I. (1997). Subliminal visual priming. Paper presented at the Sixth Annual meeting of the Israel Society for Neurosciences, Eliat, Israel, December.

Biederman, I., & Bar, M. (1997). What's the fuss about perceiving depth-rotated objects? Paper presented at the Meetings of the Psychonomics Society, Philadelphia, PA, November.

Biederman, I. (1997). Why separate fMRI loci for the recognition of faces and objects? Invited presentation at a Symposium on Neural Imaging, University of Michigan, October.

Biederman, I. (1997). Invited seminar presented at the NATO Advanced Study Institute (ASI) on 'Face Recognition: From Theory to Applications, Stirling, Scotland, UK, June 23-July 4.

M. Bar and I. Biederman. (1997). Subliminal Visual Priming. In The First Conference of the Association for the Scientific Study of Consciousness. Claremont, CA. June.

Biederman, I., & Subramaniam, S. (1997). Predicting the shape similarity of objects without distinguishing viewpoint invariant properties (VIPs) or parts. *Investigative Ophthalmology & Visual Science*, 38, 998.

Bar, M., & Biederman, I. (1997). The robustness of subliminal visual priming over time and intervening trials. *Investigative Ophthalmology & Visual Science*, 38, 1005.

Fiser, J., & Biederman, I. (1997). Independence of visual priming to hemisphere, scale, and reflection changes. *Investigative Ophthalmology & Visual Science*, 38, 1005.

Kalocsai, I., & Biederman, I. (1997). Biologically inspired recognition model with horizontal connections and extension fields. *Investigative Ophthalmology & Visual Science*, 38, 1000.

Subramaniam, S. & Biederman, I. (1997). Does contrast reversal affect object identification. *Investigative Ophthalmology & Visual Science*, 38, 998

Biederman, I. (1997). Invited address to Conference on Vision and Visual Cognition, Copenhagen, April 25-27.

Biederman, I. (1997). Invited discussant at a CIBA Foundation Workshop on Vision, London, U. K., February, 14.

Biederman, I. (1997). Neurocomputational Bases of Face and Object Recognition. Invited address presented at a Meeting on Knowledge Based Vision, The Royal Society (London), February 12-13.

Biederman, I (1996). Invited presentation at U.S. Air Force Conference on New Frontiers in Sensor Applications. Albuquerque, New Mexico. November.

Biederman, I., & Kalocsai, P. (1996). Face but not object representations preserve the original Fourier components. Paper presented at the Meetings of the Psychonomics Society, Chicago, Nov.

Kalocsai, P., & Biederman, I. (1996). Addition of horizontal connections and extension fields to a low level object recognition model qualitatively improves its performance. Paper presented at a Meeting on Object Perception and Memory, Chicago, Nov.

Bar, M., & Biederman, I. (1996). Subliminal visual priming. Paper presented at a Meeting on Object Perception and Memory, Chicago, Nov.

Fiser. J., Subramaniam, S., & Biederman, I. (1996). Coarse-to-fine tuning on object recognition: Size or scale. Paper presented at the European Conference of Visual Perception, Strasbourg, France, Sept.

Biederman, I. (1996). Applied aspects of shape recognition research. Invited address presented at the Attention & Performance Conference, Haifa, Israel, July.

Biederman, I. (1996). Perceiving function. Invited address presented at the Computer Vision Symposium. San Francisco, CA, June.

Biederman, I. (1996). A neural computational account of real-time object and face recognition. Invited paper presented to a Symposium on Cognition and Neuroscience. University of Michigan, Ann Arbor, Michigan, May.

Fiser, J., Subramaniam, S., & Biederman, I. (1996). The effect of changing size and spatial frequency content of gray-scale object images in RSVP identification tasks. *Investigative Ophthalmology & Visual Science*, 37, 178.

Kalocsai, P., Biederman, I., Fiser, J., & Fang, P. (1996). Differences between object and face recognition in utilizing early visual information. *Investigative Ophthalmology & Visual Science*, 37, 176.

Bar, M., & Biederman, I. (1996). Is subliminal priming visual? Is it translationally invariant? *Investigative Ophthalmology & Visual Science*, 37, 178.

Yokosawa, K., Subramaniam, S., Biederman, I. (1996). Independence of perceptual and semantic features in object verification. *Investigative Ophthalmology & Visual Science*, 37, 178.

O'Kane, B. L., Biederman, I., Cooper, E. E., & Kalocsai, P. (1996). Modeling parameters for target identification: Spatial filters vs. critical features. Paper presented at the IRIS conference, Monterey, CA.

O'Kane, B. L., Biederman, I., Cooper, E. E., & Kalocsai, P. (1996). Spatial filter and geon models as a biological framework for the identification of thermal signatures. Paper presented at the Meetings of the Army Science Board, Newport News, VA.

Biederman, I., & Bar, M. (1995). One-Shot Viewpoint Invariance with Nonsense Objects. Paper presented at the Annual Meeting of the Psychonomic Society, 1995, Los Angeles, November.

Kirkpatrick-Steger, K., Wasserman, E. A., & Biederman, I. (1995). Effects of deletion, movement, and scrambling of object components on picture perception in pigeons. Paper presented at the Annual Meeting of the Psychonomic Society, Los Angeles, November.

Fiser, J., & Biederman, I. (1995). Do spatial frequency and orientation information contribute similarly to visual object priming? Paper presented at the Third Annual Workshop on Object Perception and Memory. Los Angeles, Nov

Bar, M., & Biederman, I. (1995). Immediate use of viewpoint invariant information for matching depth-rotated objects. Paper presented at the Third Annual Workshop on Object Perception and Memory. Los Angeles, Nov.

Biederman, I. (1995). Recognition of Faces and Objects: Speculations on a General Theory of Shape Recognition. Invited presentation to the Workshop on Face and Object Recognition, Cardiff, Wales, Oct.

Biederman, I. (1995). A neural-computational theory of perceptual and cognitive pleasure. Invited address to the Welsh Branch of the British Psychological Society, Cardiff, Wales. Oct.

Biederman, I. (1995). Binding and object recognition. Invited paper presented at a Symposium on Phenomena and Architectures of Cognitive Dynamics. Leipzig, Germany, June.

Biederman, I., & Kalocsai, P. (1995). The psychophysics of face recognition. Invited paper at the International Workshop on Automatic Face- and Gesture-Recognition. Zurich, Switzerland, June.

Subramaniam, S., Biederman, I., Kalocsai, P., & Madigan, S. R. (1995). Accurate identification, but chance forced-choice recognition for RSVP pictures. *Investigative Ophthalmology & Visual Science*, 36, 377.

Fiser, J., & Biederman, I. (1995). Priming with complementary gray-scale images in the spatial-frequency and orientation domains. *Investigative Ophthalmology & Visual Science*, 36, 475.

Cooper, E. E., Subramaniam, S., & Biederman, I. (1995). Recognizing objects with an irregular part. *Investigative Ophthalmology & Visual Science*, 36, 473.

Kalocsai, P., & Biederman, I. (1995). Selective attention among presumed classifiers in the human face recognition system. *Investigative Ophthalmology & Visual Science*, 36, 374.

Biederman, I., Gerhardstein, P. C., & Bar, M. (1995). An inadvertent experiment fails to confirm the employment of viewpoint dependent mechanisms in human object recognition. *Investigative Ophthalmology & Visual Science*, 36, 184.

Biederman, I. (1995). From image edges to geons to viewpoint-invariant object representations. Invited address (featured speaker) presented to the Vision Society of Japan, Tokyo, January.

Biederman, I. (1995). Invited panelist. Discussion of 3D object representation in the brain. ATR Symposium on Face and Object Recognition '95, Kansai, Japan, January.

Biederman, I. (1995). Recognition of faces and objects: implications for a general theory of shape recognition. Invited presentation at the ATR Symposium on Face and Object Recognition '95, Kansai, Japan, January.

Professional recognition based on ARO supported work:

Currrent Editorial Boards: *Psychological Review, Visual Cognition, Journal of Experimental Psychology: Human Perception and Performance; and British Journal of Psychology*

Elected to the Society of Experimental Psychologists (An honor society).

Invited to be a Fellow at the Center for Advanced Study in the Behavioral Sciences, Stanford University.

Interviewed by Anne Eisenberg, University of Iowa, as one of the 15 most influential cognitive scientists in the world as determined by citation counts and peer ratings.

USC Associates Award for Creativity in Research ($5,000).

Named to give the 2001 Broadbent Lecture at the Meetings of the European Society of Cognitive Psychology to be held in Edinborough, Scotland.

1987 *Psychological Review* article, "Recognition-by-Components: A Theory of Human Image Understanding" deemed a "Classic" in a 1999 poll of visual perception scientists conducted by Professor Steven Yantis, Johns Hopkins University.

Invited to Present the Following Featured or Keynote Address at Scientific Meetings

Invited to present the Donald E. Broadbent Lecture at the European Conference on Cognitive Psychology, Edinborough, Scotland (July, 2001).
Invited Keynote Speaker, 4th Annual Southern California Joint Symposium on Neural Computation. Los Angeles, CA, May, 1997.
Invited address to the Royal Society of London, February, 1997.
IEEE Computer Vision and Pattern Recognition Conference, San Francisco, CA June, 1996 (Keynote Speaker on Workshop on Function, Formation, and Facilitation.)
Attention & Performance Conference, Haifa, Israel, July 1996. (Featured speaker.)
Meetings of the Vision Society of Japan, January, 1995. (Featured Speaker)

INVITED COLLOQUIA

Weizmann Institute, Rehovat, Israel; Claremont College; Inserm, Cerveau and Vision, Lyon France; Inserm, Strausberg, France; University of Southhampton, England; UCLA; INSERM, Strasbourg; France; University of Glasgow, Scotland; University of St. Andrews, Scotland; Catholique University of Leuvan, Belgium; Birmingham University, England; University of California, Irvine; University of Michigan; Rutgers University (Nov '97); Technische Universitaet Berlin (Dec '97); Szeged University (Hungary) (Dec '97); University of Louisville (March, '98); John Hopkins University (March, '98); Centre de Recherche Cerveau et Cognition, CNRS, Toulouse (April, '98); University of California, San Diego (Computer Science, March '99); UCLA (Cognitive Science, November, '99); University of British Columbia (Jan., '00); Simon Fraser University (Jan. '00); Claremont College, (Jan. '00); Max Planck Institute, Munich (Feb. '00); Medical University of Munich (Neurology) (Feb. '00); Department of Physiology, Katholique University of Leuven, Belgium (March, 00); CNRS Marseille, France (April, 00).

SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

József Fiser, USC Graduate Student, Computer Science, Ph. D.

Peter Kalocsai, USC Graduate Student, Psychology, Ph. D.

Suresh Subramaniam, USC Graduate Student, Psychology, Ph. D.

Moshe Bar, USC Graduate Student, Psychology, Ph. D.

Michael C. Mangini, USC Graduate Student

Edward A. Vessel, USC Graduate Student

Nancy Wang, USC Undergraduate Student in Psychobiology, B. A.

Trang Hong, USC Undergraduate Student in Psychology, B. A.

Kathy Kreuzer, USC Undergraduate Student in Political Science, B.A.

Viet Nguyen, USC Undergraduate Student in Classics

Ali Narayan, USC Undergraduate Student in Psychology

Henry Nguyen, USC Undergraduate Student in Engineering

9. INVENTIONS: None.

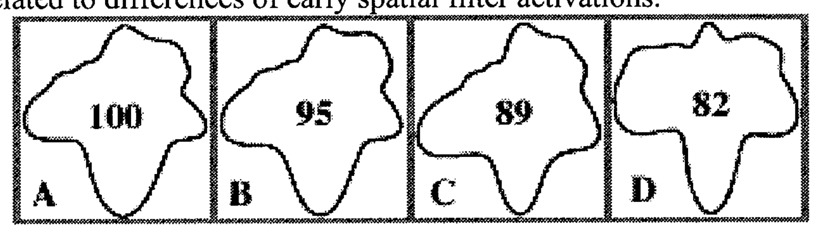
ABSTRACTS OF SELECTED PAPERS

O'Kane, B., Biederman, I., Cooper, E. E., & Nystrom, B. (1997). An account of object identification confusions. *Journal of Experimental Psychology: Applied,* 3, 21-41..

In two experiments, trained military observers identified vehicles in infrared (thermal) imagery that varied in distance, signal-to-noise ratio, and orientation. A measure of shape similarity was derived from a contingency tree which allowed prediction of the confusion rates between any two vehicles based on the number of detectable, distinguishing parts. The mean confusion rates between pairs of vehicles was strongly correlated with the nodal distance between these vehicles in the similarity trees, even though the similarity trees had been constructed without knowledge of the confusion rates. Such trees offer the possibility for substantial improvements in the modeling of human object identification and, when incorporated into training programs, offer a high potential for reducing the likelihood of identification errors.

Biederman, I., & Subramaniam, S. (1997). Predicting the shape similarity of objects without distinguishing viewpoint invariant properties (VIPs) or parts. *Investigative Ophthalmology & Visual Science*, 38, 998.

Purpose. The similarity between complex shapes such as A&B, not distinguished by NAPs or part differences, would seem to be ineffable. Would a similarity measure based on a lattice of (wavelet-like) columns of Gabor filters at different scales and orientations, presumed to be a simplified model of early filtering (Lades et al., 1993), be correlated with the actual difficulty of distinguishing among such shapes? **Methods**. The similarity of each of the 81 Shepard & Cermak (1973) toroidal "free-form" stimuli were evaluated by the Lades et al model. The similarity value, percentage of maximum similarity, is a function of the sum of the differences in the activation values of the corresponding filters. The values of the four shapes relative to A is shown. Subjects performed same-different judgments of a pair of sequentially presented shapes, with S1=250 msec, Mask(=ISI)=125 msec, S2=200 msec, Mask 125 msec. On 50% of the trials S1=S2. Similarity on different trials ranged from 68 to 95. **Results**. At high levels of similarity, above 83, RTs and error rates on negative trials were almost perfectly correlated with the similarity values, rs=.96 and .95, respectively. Below 83, RTs were moderately related (r=.65), to similarity and errors were near floor. **Conclusion**. A similarity measure roughly characteristic of early cortical stage (V1 or V2) filtering provides an excellent measure of the similarity of highly similar complex shapes. Slightly less similar shapes can activate different structural descriptions, e.g., "straight vs. curved big lobe," for a pair of objects, and render similarity less related to differences of early spatial filter activations.



Biederman, I., & Kalocsai, P. (1997). Neurocomputational bases of object and face recognition. *Philosophical Transactions of the Royal Society London: Biological Sciences*, 352, 1203-1219.

Abstract. A number of behavioral phenomena distinguish the recognition of faces and objects, even when members of the set of objects are highly similar. Because faces have the same parts in approximately the same relations, individuation of faces typically requires specification of the metric variation in a holistic and integral representation of the facial surface. The direct mapping of a hypercolumn-like pattern of activation onto a representation layer that preserves relative spatial filter values in a 2D coordinate space, as proposed by C. von der Malsburg and his associates (Lades et al., 1993; Wiskott, et al., 1997), may account for many of the phenomena associated with face recognition. An additional refinement, in which each column of filters (termed "a jet") is centered on a particular facial feature (or fiducial point), allows selectivity of the input into the holistic representation to avoid incorporation of occluding or nearby surfaces. The initial hypercolumn representation also characterizes the first stage of object perception, but the image variation for objects at a given location in a 2D coordinate space may be too great to yield sufficient predictability directly from the output of spatial kernels. Consequently, objects can be represented by a structural description specifying qualitative (typically, nonaccidental) characterizations of an object's parts, the attributes of the parts, and the relations among the parts, largely based on orientation and depth discontinuities (e.g., Hummel & Biederman, 1992). A series of experiments on the name priming or physical matching of complementary images (in the Fourier domain) of objects and faces documents that whereas face recognition is strongly dependent on the original spatial filter values, object recognition evidences strong invariance to these values, even when distinguishing among objects that are as similar as faces.

Biederman, I., Subramaniam, S., Bar, M., Kalocsai, P, & Fiser, J. Subordinate-Level Object Classification Reexamined. (1998). *Psychological Research*, 62, 131-153.

Abstract. The classification of table as round rather than square, a car as a Mazda rather than a Ford, a drill bit as 3/8 inch rather than 1/4 inch, and a face as Tom, have all been regarded as a single process termed "subordinate classification." Despite the common label, the considerable heterogeneity of the perceptual processing required to achieve such classifications requires, minimally, a more detailed taxonomy. Perceptual information relevant to subordinate level shape classifications can be presumed to vary on continua of: a) the type of distinctive information that is present, nonaccidental or metric, b) the size of the relevant contours or surfaces, and c) the similarity of the to-be-discriminated features, e.g., whether a straight contour has to be distinguished from a contour of low curvature vs. high curvature. We consider three, relatively pure, cases. Case 1 subordinates may be distinguished by a representation, a geon structural description (GSD), specifying a nonaccidental characterization of an object's large parts and the relations among these parts, such as a round table vs. a square table. Case 2 subordinates are also distinguished by GSDs, except that the distinctive GSDs are present at a small scale in a complex object so the location and mapping of the GSDs are contingent on an initial basic-level classification, as when we use the logo to distinguish various makes of cars. Expertise for Cases 1 and 2 can be easily achieved through specification, often verbal, of the GSDs. Case 3 subordinates, which have furnished much of the grist for theorizing with "view-based" template models, require fine metric discriminations. Cases 1 and 2 account for the overwhelming majority of shape-based basic- and subordinate-level object classifications that people can and do make in their everyday lives. These classifications are typically made quickly, accurately, and with only modest costs of viewpoint changes. Whereas the activation of an array of multiscale, multiorientation filters, presumed to be at the initial stage of all shape processing, may suffice for determining the similarity of the representations mediating recognition among Case 3 subordinate stimuli (and faces), Cases 1 and 2 require that the output of these filters be mapped to classifiers that make explicit the nonaccidental properties, parts, and relations specified by the GSDs

Bar, M., & Biederman, I. (1999). One-shot viewpoint invariance in matching novel objects. *Vision Research*, 39, 2885-2899..

Humans show an extraordinary competence at recognizing objects from arbitrary orientations in depth. According to one class of theories, this competence is based on previously having learned different templates, expressing the metric properties (MPs) at the different orientations. An alternative class of theories assumes that nonaccidental properties (NAPs) can be exploited so that even novel objects can be recognized under depth rotation. Same-Different judgments of a sequential pair of novel rotated objects, differing in a MP or a NAP (when different), viewed only once by each subject, revealed complete depth invariance when objects differed in a NAP. Rotation dramatically reduced the detectability of MP differences to a level well below that expected by chance. NAPs offer a striking advantage over MPs for object classification and are therefore more likely to play a central role in the representation of objects.

Subramaniam, S., Biederman, I., & Madigan, S. A. (2000). Accurate identification but no priming and chance recognition memory for pictures in RSVP sequences. *Visual Cognition*, 7, 511-535.

Abstract. In 1969, Potter and Levy reported that recognition memory of accurately perceived RSVP pictures was extremely low, an effect that they attributed to disruption of memory consolidation. Here we report that the repetition of an RSVP picture (72-126 msec/picture) up to 31 times prior to when it became a target had no effect on identification accuracy. At these rates, forced choice recognition memory was at chance. Single presentations of the pictures outside of the RSVP sequences readily resulted in substantial priming of their identification within the sequences. We offer a neural interpretation of Potter and Levy's explanation, as well as contemporary two-stage accounts of RSVP memory and attentional phenomena, based on the recent finding (Tovee & Rolls, 1995) that most of the information in inferior temporal cells is conveyed in the first 50 msec of firing but the cells continue their activity for an additional 350 msec. The additional activity, by our account, is required for memory and it is this activity that may be disrupted by attention to the next image during RSVP presentations. The critical factor for priming, if not memory in general, may be attention to the stimulus for a few hundred msec beyond that which is required for its identification. Single trial presentations thus manifest robust memory and priming effects—even when the stimulus cannot be identified---while RSVP conditions in which the stimulus can be identified result in poor memory.

Bar, M., & Biederman, I. (1998). Subliminal visual priming. *Psychological Science*, 9, 464-469.

Masked pictures of objects were flashed so briefly that only 13.5% of them could be named. Forced-choice accuracy for the unidentified objects was at chance. When shown again, about 15 minutes and 20 intervening trials later, without any indication of possible repetitions, identification accuracy increased to 34.5%. The priming was completely visual, rather than semantic or verbal, as there was no priming of same name-different shaped images. This is the first demonstration of facilitatory visual recognition priming by unidentified pictures when the subject could not anticipate if, when, or where the previously unidentified picture was to be shown again. A change in the position of the object reduced but did not eliminate the priming, allowing a speculation that the locus of subliminal visual priming is at an intermediate stages in the ventral cortical pathway for shape recognition.

Bar, M., & Biederman, I. (1999). Localizing the cortical region mediating visual awareness of object identity. *Proceedings of the National Academy of Sciences*, 96, 1790-1793.

Presentations of pictures that are too brief to be recognized, or even guessed above chance on a forced-choice test, can nonetheless facilitate the recognition of the same pictures many trials later. This subliminal visual priming was compared for images translated 4.8° either between or within quadrants of the visual field. Priming was evident only for images that remained within the same quadrant on priming and test trials. Consequently, subliminal visual priming is likely mediated by cortical areas in which a substantial portion of the cells have receptive fields (RFs) large enough to respond to both presentations of a stimulus translated almost 5° yet where the RFs are confined to a single quadrant, viz., the human homologue of macaque V4 or TEO (the posterior part of the inferior temporal cortex). Awareness of object identity might therefore be associated exclusively with activity at or beyond the anterior part of the inferotemporal cortex.

Vogels, R., Biederman, I., Bar, M, & Lorincz, A. (2000). Inferior temporal neurons show greater sensitivity to nonaccidental than metric differences. *Journal of Cognitive Neuroscience*, In press.

It has long been known that macaque inferior temporal (IT) neurons tend to fire more strongly to some shapes than to others and that other neurons can show markedly different shape preferences. Beyond the discovery that these preferences can be elicited by features of moderate complexity, no general principle of (non-face) object recognition had emerged by which this enormous variation in selectivity could be understood. Computational as well as psychophysical work suggests that one such principle is the difference between view-invariant, non-accidental (NAP) and view-dependent, metric shape properties (MPs). We measured the responses of single IT neurons to objects differing in either a NAP or a MP of a single part, shown at two orientations in depth. The cells were more sensitive to NAP than MP changes, even when the image variation produced by the former were smaller than the latter. Multidimensional scaling of the neural responses indicated a NAP/MP dimension, independent of an orientation dimension. The present results thus demonstrate that a significant portion of IT's neural code represents differences in NAPs rather than MPs. This code may enable a) immediate recognition of novel objects at new views, and b) "object constancy," the subjective phenomena that objects undergoing depth rotation do not appear to change their shape despite dramatic changes in the retinal image produced by such rotations.